Operation, Calibration, Georectification, and Reflectance Inversion of NASA's Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) Four- and Two-Meter Data Acquired from a Low-Altitude Platform

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ABSTRACT

In late 1997, NASA approved a demonstration plan to collect high-spatial-resolution AVIRIS spectral images from a low-altitude airborne platform. The objective of this effort was to explore the different, and perhaps higher, information content of AVIRIS spectra at the 4-meter spatial scale for science research and applications. Strict requirements were placed on the effort to control risks to the AVIRIS instrument and maintain continued operational capability on the nominal ER-2 high-altitude airborne platform. Components of the effort included aircraft selection as well as development of new mechanical, electrical, navigation, ground support, installation, operations, and software subsystems for the low-altitude demonstration. On 28 September 1998 AVIRIS flew on a Twin Otter aircraft, measuring spectral images with 4-meter spatial resolution. In the following 7 weeks, AVIRIS operated on this low altitude platform measuring data for a range of investigation across the United States. This paper presents key aspects of the implementation, operation, calibration, georectification, and validation of AVIRIS on a low-altitude platform in the Autumn of 1998.

1. INTRODUCTION

The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) is an Earth-looking imaging spectrometer designed and operated by the NASA Jet Propulsion Laboratory in California (Green et al 1998). AVIRIS measures the total upwelling spectral radiance from 400 to 2500 nm through 224 imaging channels with spectral sampling intervals and response functions of nominally 10 nm. Historically AVIRIS has acquired data from the Q-bay of a NASA ER-2 aircraft at an altitude of 20 km with 20-meter spatial resolution on the ground and an 11-km cross track swath. Complete spectral, radiometric and spatial calibrations for each of the 224 channels are determined and maintained through each operational period. These data are currently used for investigations spanning: terrestrial ecology, geology, agriculture, biomass burning, coastal and inland waters, the atmosphere, snow and ice hydrology, environmental hazards, algorithm development, and spaceborne sensor calibration.

In 1997 a plan was approved to demonstrate operation of the AVIRIS instrument on a low-altitude aircraft platform. Operation at a low altitude allows collection of AVIRIS data with high spatial resolution to expand support of existing investigations as well as to explore new issues associated with finer spatial scales. There were four key elements to the plan. First, the AVIRIS instrument would not be modified in any significant way.

This required an infrastructure that would allow AVIRIS to operate in the native ER-2 configuration on the low-altitude airborne platform. To maximize operations flexibility, the goal for transition time between aircraft was one day. Second, installation and operation on the low-altitude aircraft would be specifically designed to avoid additional risk to the AVIRIS instrument. Third, the transition between ER-2 and low-altitude aircraft would not require laboratory recalibration. Fourth, AVIRIS data collected on the low-altitude platform would be at the ER-2 level of spectral and radiometric quality and calibration accuracy. These elements focused and constrained design and implementation of the plan. This paper describes aspects of the platform selection, engineering implementation, calibration, georectification and algorithm testing associated with operation of AVIRIS on a low-altitude platform in 1998.

2. THE LOW-ALTITUDE AIRBORNE PLATFORM

Early in the AVIRIS low-altitude demonstration activity, a number of specific requirements were established for selecting the airborne platform. The primary requirement was that the aircraft have a door large enough to allow installation of the AVIRIS instrument. The external dimensions of AVIRIS are 1.6 by 1.4 by 0.9 meters. Next the aircraft center of gravity range as well as electrical power availability needed to be sufficient for AVIRIS. AVIRIS has a mass of 350 kg and requires nominally 40 A of 28 VDC, 10 A of 110 VAC at 400 Hz, and 5 A of 110 VAC at 60 Hz. The next requirement was that the aircraft be able to fly at a height-to-velocity ratio that allowed acquisition of properly sampled imagery. On the ER-2 aircraft AVIRIS flies at 65,000 ft and 410 knots. This translates to a speed of 75 knots at 10,000 ft above ground level. Table 1 gives the range of flight altitudes and ground speed desired for the AVIRIS low-altitude platform. An essential requirement was that the aircraft have a down-looking hatch through which AVIRIS would measure spectral images. The hatch dimensions needed to be large enough to accommodate the AVIRIS 30-degree field of view. The final requirements were that the aircraft be reasonably available and of reasonable cost to use. With these criteria a list of possible aircraft types was assembled, ranging from a four-engine C-130 transport to a two-engine DHC-4 Caribou. Following a review of the options identified, the DHC-6 Twin Otter was selected. A picture of a Twin Otter is given in Figure 1. Versions of the Twin Otter were available from several sources that would satisfy all of the necessary criteria for AVIRIS to measure spectral images at high spatial resolution. A Twin Otter available from the National Oceans and Atmospheric Administration (NOAA) was selected as the specific aircraft in 1998.

Table 1. Desired altitude and ground speed for the AVIRIS low-altitude platform.

Altitude, Feet	Speed, Knots	Resolution, Meters		Altitude, Feet	Speed, Knots	Resolution, Meters
65000	410	20		14000	88	4.3
24000	151	7.4		12000	76	3.7
22000	139	6.8		10000	63	3.1
20000	126	6.2		8000	51	2.5
18000	114	5.5		6000	38	1.9
16000	101	4.9				

Figure 1. A DHC-6 Twin Otter aircraft.

3. AVIRIS LOW-ALTITUDE INFRASTRUCTURE

A significant amount of new infrastructure was required to enable the operation of AVIRIS on the Twin Otter aircraft. This infrastructure spanned the mechanical, electrical, navigation, ground support, installation, operations, and software subsystems of AVIRIS. The primary underlying requirement of this effort was that AVIRIS be able to transition between the ER-2 and the Twin Otter in 24 hours. To achieve this requirement a series of interfaces that mimicked those of the ER-2 needed to be developed and installed in the Twin Otter. A mechanical mounting structure was developed that attached to the seat rails and rear bulkhead of the Twin Otter. With the assistance of NOAA, this structure was designed to support AVIRIS up to a maximum 9 g forward and 3 g vertical load. AVIRIS attached to this structure in the same manner as in the ER-2. For power, a set of electrical inverters were adapted to convert power available on the Twin Otter to the power requirements of AVIRIS on board the ER-2. Because more turbulence is encountered in the lower atmosphere, an inertial navigation/global positioning (INS/GPS) system was procured and installed on AVIRIS to acquire both position and pointing data at high precision and accuracy. This new subsystem replaced the navigation data stream that was provided from the ER-2 aircraft. A new set of lightweight and compact ground support equipment was developed to support AVIRIS in the Twin Otter. This ground support equipment was required to fly along with AVIRIS from airport to airport. Key components of this ground support equipment included a modern portable computer, a pair of rugged liquid nitrogen dewars, and a portable high-throughput dehumidifier. Installation of AVIRIS in the Twin Otter required development of detachable set of wheels that would allow AVIRIS to be rolled from a forklift platform into the Twin Otter and positioned over the observation hatch. Figure 2 shows AVIRIS on the forklift platform prior to installation. Figure 3 shows AVIRIS inserted through the door of the NOAA Twin Otter. Figure 4 shows AVIRIS fully installed in the rear of the Twin Otter. In the passenger area of the Twin Otter, an ER-2 cockpit simulator was installed to allow the AVIRIS experiment coordinator to start the AVIRIS instrument and control the recording of AVIRIS spectral image data. A new set of operations procedures were developed to orchestrate the preflight preparation of AVIRIS, the acquisition of data in flight, the postflight recovery of the high-density flight tape, and the navigation data. New operations software was developed for the ground support computer that traveled with AVIRIS. At the JPL AVIRIS data subsystem new calibration software was developed that took advantage of independently developed georectification software modules (Boardman 1998).

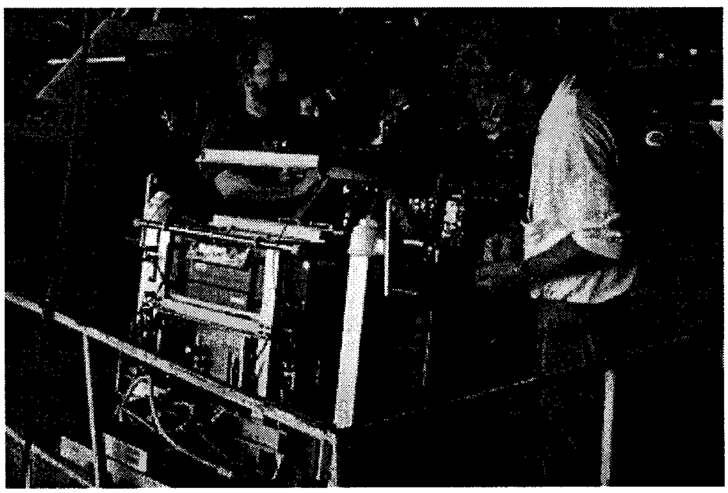

Figure 2. Preparation of AVIRIS for installation into the Twin Otter aircraft.

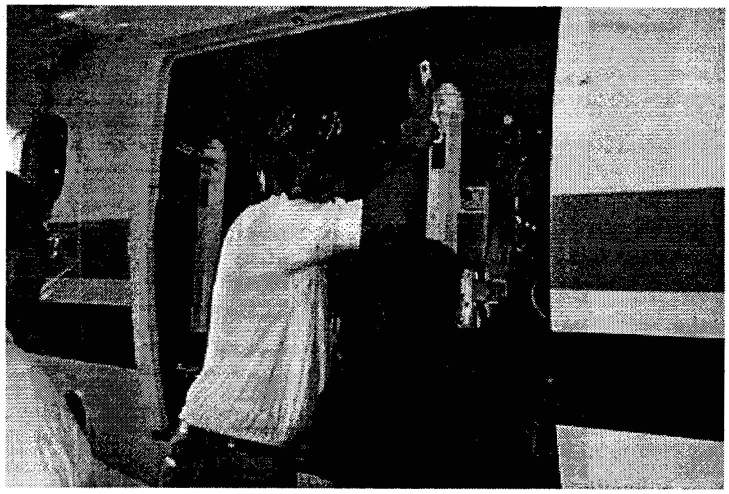

Figure 3. Installation of AVIRIS through the large door in the Twin Otter aircraft.

Figure 4. AVIRIS installed in the back of the Twin Otter aircraft.

4. CALIBRATION AND VALIDATION

The primary objective for operating AVIRIS on a low-altitude platform was measurement of calibrated spectral images at high spatial resolution. To ensure this objective was achieved, the first flight of AVIRIS on the Twin Otter was dedicated to an inflight calibration experiment. This experiment was orchestrated in California at Rogers Dry Lake, adjacent to the NASA Dryden Flight Research Center on 28 September 1998. In most respects the inflight calibration experiment was the same as those performed to validate the calibration of AVIRIS on the ER-2 platform (Conel et al, 1988, Green et al, 1996, Green et al, 1999). A 40- by 8-meter calibration target was established on the dry lake surface. The calibration target area was demarced by a large blue plastic tarp at each end. The spectral reflectance of the calibration target was measured at the time of the

AVIRIS overflight. Atmospheric optical depths and water vapor were measured at the nearby Dryden Flight Research Center. These measurements of surface reflectance and atmospheric parameters were used to constrain the MODTRAN radiative transfer code (Berk et al 1989) and predict the radiance incident at AVIRIS.

The spectral image data acquired by AVIRIS were extracted from the high-density flight tape. The two blue plastic tarps used to locate the calibration target were identified in the AVIRIS image, as shown in Figure 5. The AVIRIS data were passed through the calibration software of the AVIRIS data calibration subsystem at the Jet Propulsion Laboratory. An average spectrum was extracted for the calibration target. Initial inspection of the AVIRIS spectrum showed that the B spectrometer was not functioning. A review of the AVIRIS preflight process revealed there had been difficulty filling the liquid Nitrogen dewar of the B spectrometer. Also, during initial comparison of the AVIRIS-measured and MODTRAN-predicted spectrum, a discrepancy of about 5 percent was noted across the entire spectrum. This discrepancy was caused by the absence of the AVIRIS hatch window. On the ER-2 AVIRIS images are measured through a hatch window, but on the Twin Otter, an open aperture with a shutter is used. The absence of the hatch window improved the throughput and signal-to-noise ratio of AVIRIS by about 5 percent. The AVIRIS calibration software was modified to exclude the transmission of the hatch window for low-altitude data. Figure 6 shows the comparison of the AVIRIS-measured spectrum and the MODTRAN-predicted spectrum for this calibration experiment. Examination of the AVIRIS onboard calibrator data early in the flight showed that the B spectrometer had been performing nominally before running out of liquid nitrogen. The average absolute agreement between the AVIRIS-measured and the MODTRAN-predicted spectra radiance was 96 percent, excluding the strong water vapor absorption and the B spectrometer regions. After explaining the anomalies this inflight calibration experiment showed that AVIRIS was as well calibrated on the Twin Otter as on the ER-2.

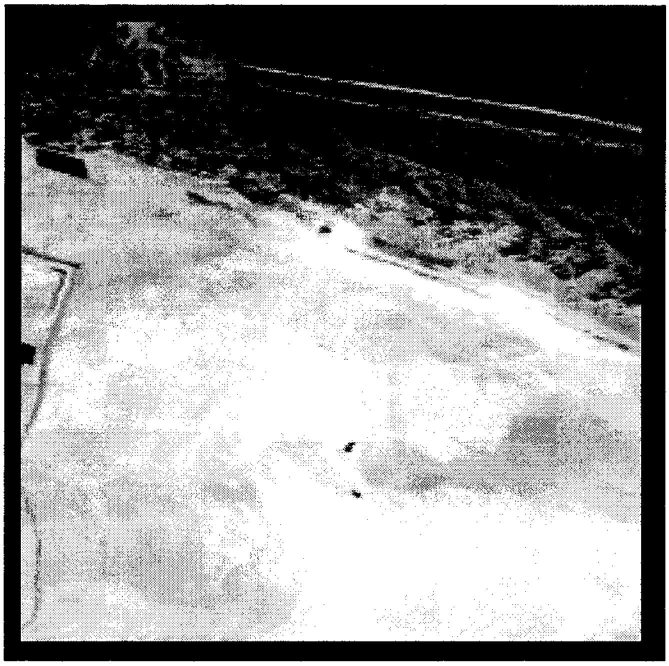

Figure 5. AVIRIS image of calibration target from Twin Otter aircraft. The target is between the two dark demarcation tarps on Rogers Dry Lake, CA.

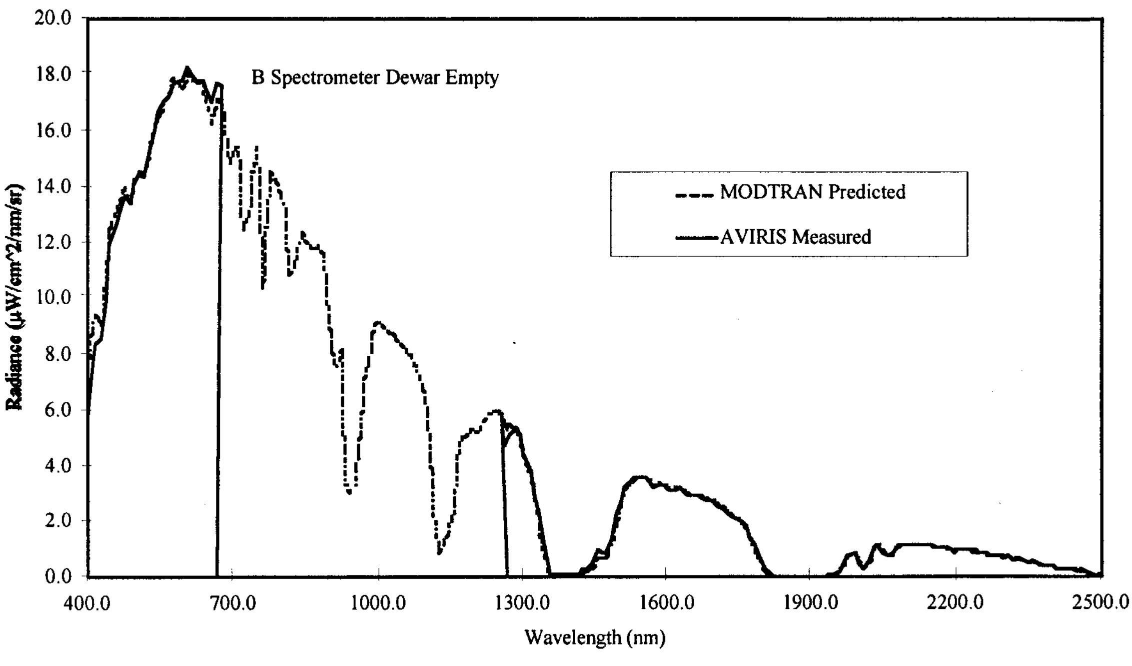

Figure 6. Results of the AVIRIS low-altitude inflight calibration experiment on 28 September 1998.

5. GEORECTIFICATION

Early on in the effort georectification was identified as essential in order to deliver high quality AVIRIS data from a low-altitude platfom. In general the atmosphere is significantly more turbulent at 12,000 ft than at 65,500 ft of altitude. Figure 7 shows effects of aircraft motion due to atmospheric turbulence on the first Twin Otter AVIRIS data set acquired on 28 September 1998. Data from the new INS/GPS system installed on AVIRIS for the Twin Otter missions was used with georectification software (Boardman 1998) to correct the AVIRIS data. Figure 8 shows the geometrically corrected AVIRIS data for the 28 September 1998 data set. Together the navigation measurements and georectification software worked better than expected given the complexity of the geometric correction problem from the Twin Otter aircraft.

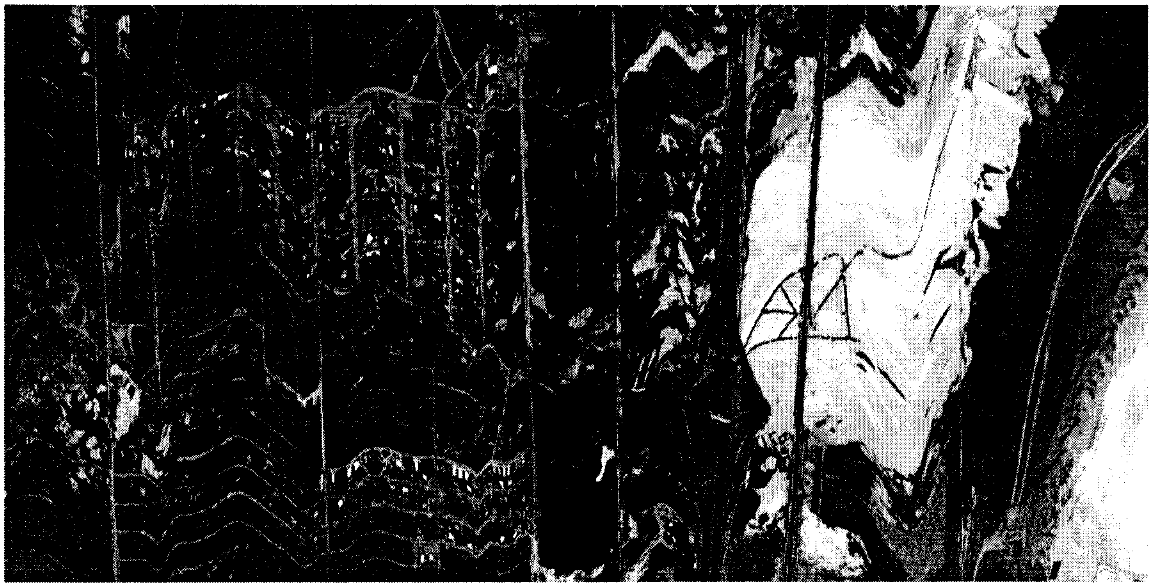

Figure 7. Ungeorectified AVIRIS imagery from north of Rogers Dry Lake, CA.

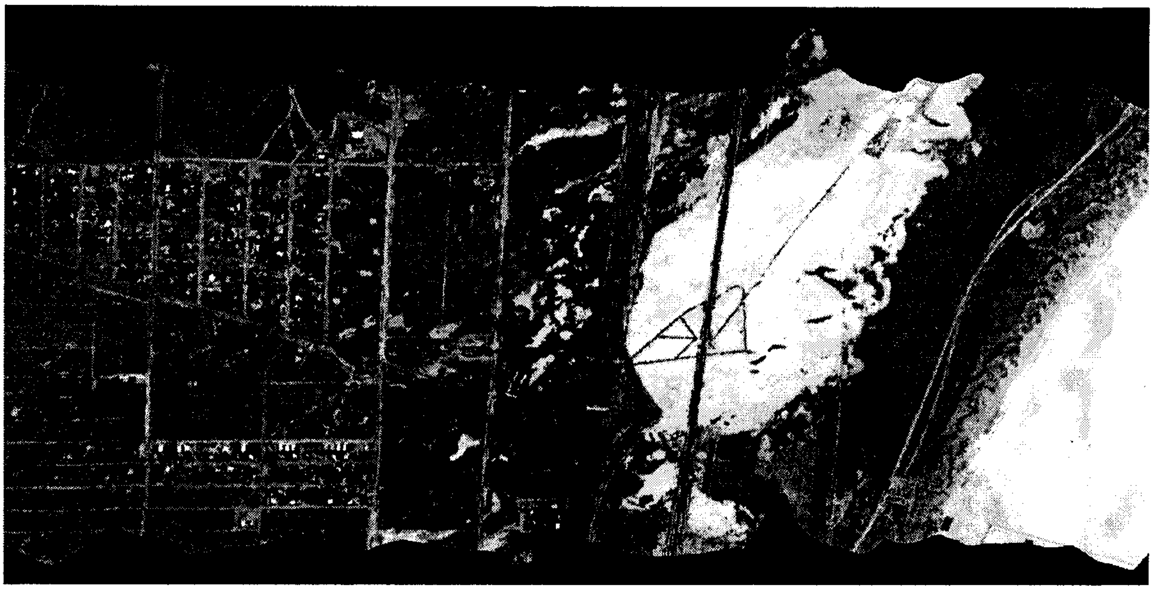

Figure 8. Georectified AVIRIS imagery from north of Rogers Dry Lake, CA.

6. REFLECTANCE INVERSION

To further validate the calibration and quality of AVIRIS spectral image data measured from the Twin Otter, several data sets were passed through a radiative-transfer-based reflectance inversion algorithm. To work correctly, the radiance-to-reflectance inversion algorithm requires spectral image data that is well calibrated and has a high signal-to-noise ratio. The data set selected for testing was acquired over Harrisburg Airport, PA. The flight altitude for this data was 6000 ft above ground level, which produced 2-meter spatial resolution data. The data were acquired while flying into a headwind so that a nearly 2-meter sampling was achieved. The image of Harrisburg Airport is shown in Figure 9. The high spatial resolution is seen through the complete resolution of the shapes of the aircraft on the tarmac. This data set was initially calibrated and georectified in the AVIRIS data subsystem. Figure 10 shows a set of five calibrated radiance spectra extracted from this data set. A radiance-to-reflectance inversion algorithm (Green et al 1991, Green et al 1993) that uses the MODTRAN radiative transfer code was applied to the AVIRIS radiance data. The derived reflectance spectra for the five extracted radiance spectra are shown in Figure 11. The good compensation of atmospheric absorption features, the solar spectrum, and atmospheric scattering demonstrate that the AVIRIS Twin Otter spectral image data support radiative-transfer-based reflectance inversion.

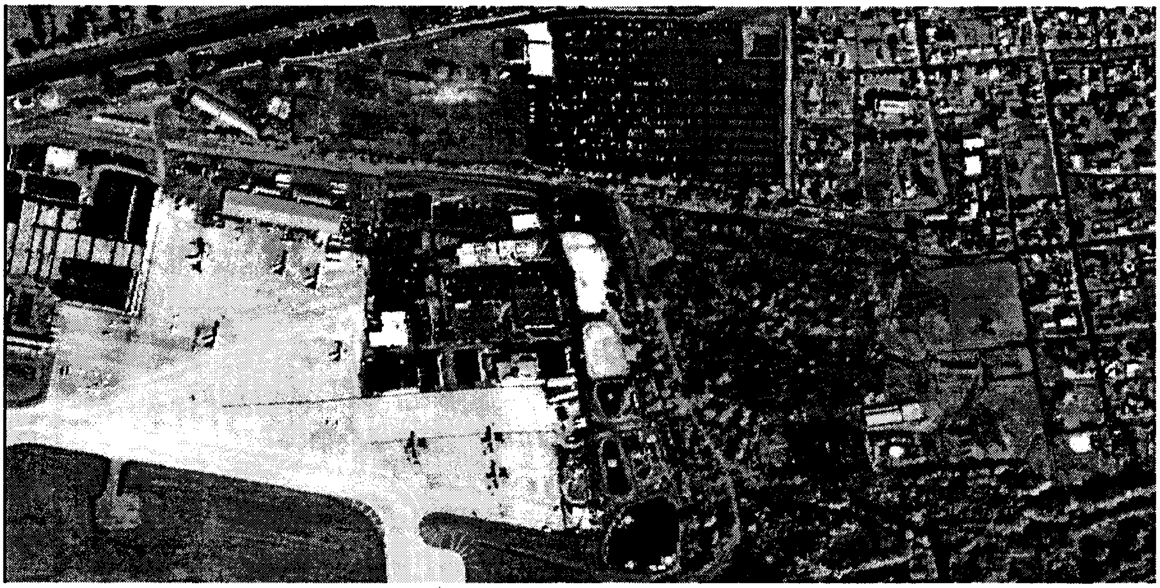

Figure 9. Low-altitude AVIRIS imagery of the Harrisburg Airport, PA.

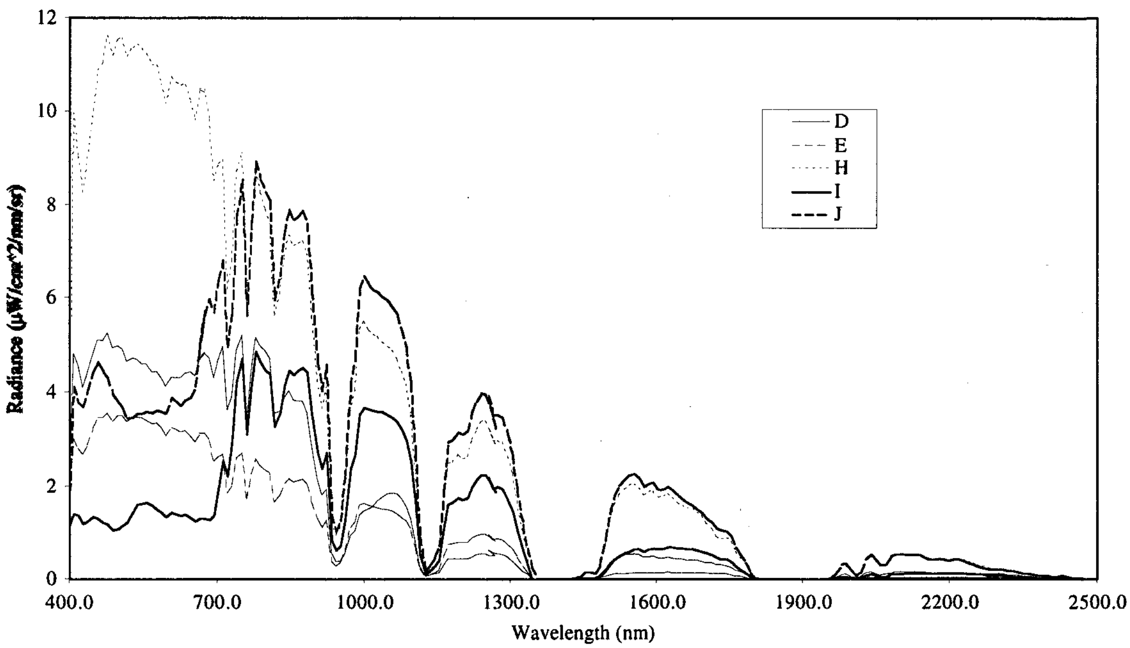

Figure 10. Calibrated Radiance spectra from the Harrisburg Airport, PA.

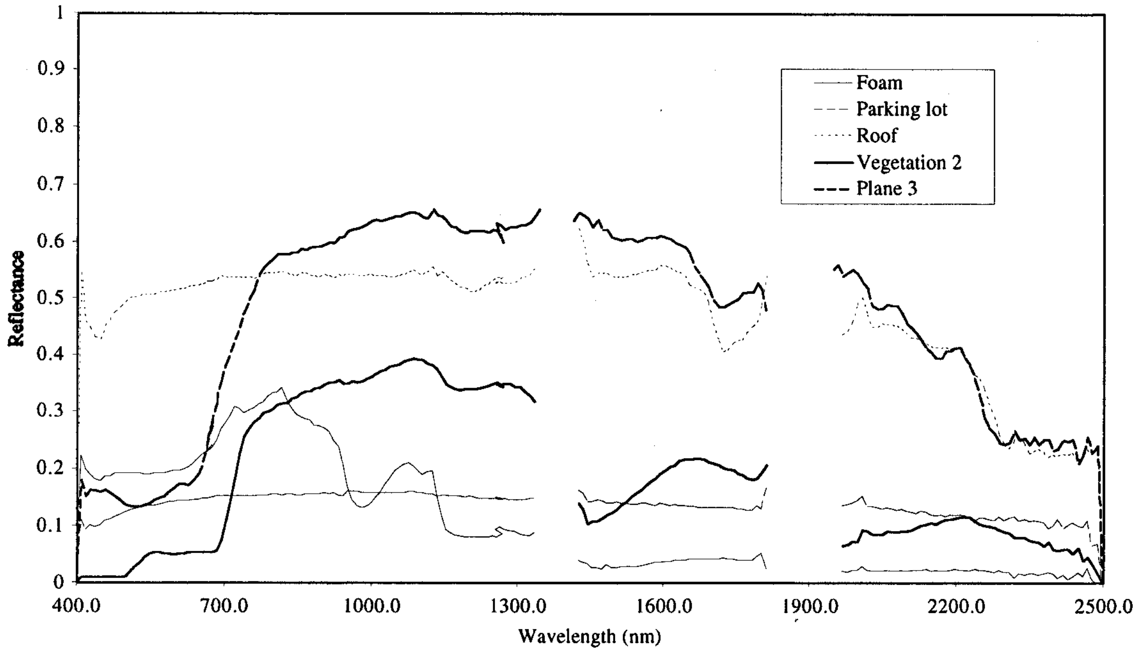

Figure 11. AVIRIS-derived apparent reflectance spectra from the Harrisburg, PA Airport.

7. DISCUSSION

The plan to demonstrate the operation of AVIRIS on a low-altitude airborne platform was ambitious. All preparation activities were required to occur in parallel with all AVIRIS ER-2 operation activities in the winter and summer of 1998. The AVIRIS team sustained this challenging balance and AVIRIS was successfully flown on the NOAA Twin Otter on 28 September 1998. AVIRIS operated on the Twin Otter for nearly 7 weeks. During this time AVIRIS acquired 243 flight lines totaling 217 gigabytes of high-spatial-resolution AVIRIS data. AVIRIS flight lines were measured across the United States—from California, Wyoming, Mississippi, New Hampshire, Florida, as well as many other locations.

While the overall experiment was thoroughly successful, some important lessons were learned. The implementation of the new INS/GPS for the low-altitude acquisitions was not completely successful. For some of the low-altitude flight lines, no navigation data were recorded. In addition, during the low-altitude operations period, a leak developed in the B spectrometer dewar, causing a fraction of the flight lines not to have data for this portion of the AVIRIS spectral range. The leak was difficult to detect and repair in the operational environment of the Twin Otter. Plans are in place to address both of these issues with a more robust implementation of the INS/GPS in 1999, and with a more extensive set of ground support equipment to travel with AVIRIS on the Twin Otter. The flexibility of the Twin Otter to takeoff and land at almost any airport enabled a high yield of data for investigators in a short time period from across the United States. This flexibility also complicated the operations planning and mission logistics. Work is ongoing to adapt the AVIRIS operations planning and mission logistics to the flexibility of the Twin Otter airborne platform. These lessons and observations are being taken into account for planning future operations of AVIRIS on the Twin Otter in 1999 and 2000.

8. CONCLUSION

In 1997 a plan was approved to operate the AVIRIS instrument on a low-altitude platform to measure imaging spectrometer data with spatial resolutions from 2 to 6 meters. The objective of the plan was to provide a new class of spatial data to existing AVIRIS investigators and to open opportunities for new investigations that required data of higher spatial resolution. The strict requirements of the plan were that the AVIRIS sensor not be modified significantly, that there be no new risks to AVIRIS, that the transition time between airborne platforms be short, and that the high quality of AVIRIS data be maintained. With these requirements a low-altitude airborne platform was identified and the mechanical, electrical, navigation, ground support, installation, operational, and software subsystems were developed to enable operation of AVIRIS from a low-altitude platform. On 28 September 1998 AVIRIS flew for the first time on a low altitude Twin Otter aircraft, measuring spectral image data with 4-meter spatial resolution. On the first flight, the calibration of AVIRIS on the Twin Otter was investigated, assessed and validated with an inflight calibration experiment. New software modules were developed and implemented in the AVIRIS data subsystem that allowed georectification of the low-altitude AVIRIS data. As a further validation, low-altitude AVIRIS data were inverted from radiance to reflectance using the MODTRAN radiative transfer code method. In 1998 AVIRIS was operated on the Twin Otter from 28 September to 18 November, measuring data for investigators across the United States. The overall objective of this effort was to develop a low altitude capability to acquire and deliver high spatial resolution AVIRIS data to investigators. This objectivewas achieved. Retrospective analyses of the Autumn 1998 low-altitude operations are being used to prepare for planned operation on the Twin Otter in 1999 and 2000.

9. REFERENCES

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